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**IGNITION AND FIRE SUPPRESSION IN AERO-
SPACE VEHICLES (PHASE II)**

Ralph J. Cato, et al

Bureau of Mines

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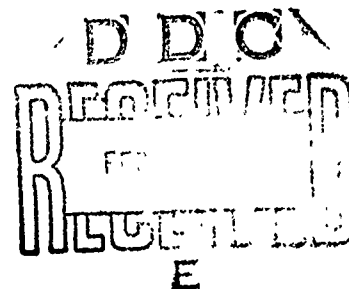
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Ralph J. Cato
George H. Martindill
Joseph M. Kuchta

Bureau of Mines
PMSRC Report No. 4178



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13. ABSTRACT		
<p>The effectiveness of Halons 1301 (CF_3Br), 1202 (CF_2Br_2), and 1211 (CF_3ClBr) as possible explosion suppressants for aircraft fuel tanks was investigated in ignitions with small charges of an IM-11 incendiary powder ($\text{Ba}(\text{NO}_3)_2\text{-Mg-Al}$) and 30-caliber incendiary ammunition. Ignitions with the incendiary powder in a 74 gallon fuel tank indicated that over 8 volume percent Halon 1301 is required to fully quench flame propagations of near-stoichiometric n-pentane-air mixtures and limit the pressure rises to less than 5 psi; such high Halon concentrations were also required under gun firing conditions using the 30-caliber ammunition. The critical Halon requirements for quenching the incendiary ignitions of n-pentane-air mixtures did not appear to differ greatly for the three Halons investigated in this work.</p> <p>Other experiments were conducted in a 216 ft³ chamber to evaluate the effectiveness and toxicity hazard of Halon 38 (C_3F_8) in extinguishing Class A fires by the total flooding mode. This agent was less effective and produced a greater toxicity hazard than Halon 1301 (CF_3Br) in extinguishing cotton sheeting or paper sheeting fires. Approximately 10 to 12 volume percent Halon 38 was required for extinguishing cotton sheeting fires, although incandescent burning was possible after extinguishment in some cases. Product HF concentrations were as high as 2500 ppm, depending upon the extinguishing conditions. Some comparison data are also given from total flooding experiments with liquid nitrogen, which was much less effective than Halon 38 in extinguishing cotton sheeting fires.</p>		

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FOREWORD

This report was prepared by the Pittsburgh Mining and Safety Research Center of the U. S. Bureau of Mines under USAF Contract No F33615-72-M-5000. The contract was initiated under Project 3048, "Fuels, Lubrication, and Fire Protection," Task 304807, "Aerospace Vehicle Fire Protection." It was administered under the direction of the Air Force Aero Propulsion Laboratory, with Mr. Robert G. Clodfelter (AFAPL/SFH) acting as project engineer.

This report summarizes the work recently completed under this contract during the period 1 December 1971 to 31 June 1972.

Dr. Robert W. Van Dolah was the administrator for the U.S. Bureau of Mines and Messrs. Joseph M. Kuchta, Ralph J. Cato, George H. Martindill, Irving Spolan, and John D'Auria actively participated in this work at the U.S. Bureau of Mines, Pittsburgh Mining and Safety Research Center, Bruceton, Pennsylvania.

This report was submitted by the authors September 1972.

This technical report has been reviewed and is approved.



ROBERT G. CLODFELTER
Chief, Fire Protection Branch
Fuels and Lubrication Division

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INTRODUCTION

This report summarizes work completed under Contract F33615-72-M-5008 "Research on Advanced Aircraft Fire Prevention Techniques" which is directed to the enhancement of fire protection capability on aerospace vehicles. Under a previous Air Force contract, investigations were conducted to evaluate various chemical flame inhibitors as possible ignition suppressants and to determine the effectiveness and toxicity hazard of Halon 1301 in the extinguishment of Class A fires.^{1,2/} Similar investigations were carried out in the present work, which was divided into three separate parts:

- I. Ignition Inhibitors for Fuel Tank Protection
- II. Total Flooding Fire Suppression Systems
- III. Safety Manual for Aircraft Accident Investigations

Under Part I, the ignition suppression effectiveness of Halons 1301 (CF_3Br), 1202 (CF_2Br_2), and 1211 (CF_2ClBr) was determined in simulated fuel tank ignitions to extend the data previously obtained under laboratory-scale conditions. The critical inhibitor requirements were defined using n-pentane-air-Halon mixtures that were ignited with small charges of an incendiary powder (IM-11), a 50-50 mix of barium nitrate and magnesium-aluminum powders. Comparison data from gun firings with 30-caliber incendiary ammunition are also presented. Under Part II, Halon 3800 (C_3F_8) was evaluated as a possible extinguishant for use on advanced aircraft. The effectiveness and toxic product formation of this agent were determined in total flooding experiments with Class A fires involving cotton or paper sheeting. Since liquid nitrogen may be available on some aircraft for inerting fuel tanks, a few total flooding experiments were also made to cursorily examine its limitations against Class A fires. However, because of the Bureau's pressing commitments to mine safety problems, it was necessary to reduce the scope of the contract and to terminate the experimental work earlier than planned.

The work under Part III, which is concerned with the preparation of a safety manual for use in investigating aircraft fires or explosions, is being treated separately and will be completed during the next year.

-
- ^{1/} Martindill, G. H., I. Spolan, and J. M. Kuchta. Fire Suppression for Aerospace Vehicles, Technical Report AFAPL-TR-70-39 (BuMines S4137), July 1970, 24 pp.
 - ^{2/} Kuchta, J. M., R. J. Cato, G. H. Martindill, and I. Spolan. Ignition and Fire Suppression in Aerospace Vehicles, Technical Report AFAPL-TR-71-93 (BuMines Report No. 4164), December 1971, 38 pp

EXPERIMENTAL APPARATUS AND PROCEDURES

A. Ignition Inhibitors for Fuel Tank Protection

The incendiary ignition experiments with the various fuel vapor-air-inhibitor mixtures were performed in a 74-gallon fuel tank, 27-inches in diameter and 30 inches long, that was constructed from the mid-section of a 450-gallon aircraft fuel tank. Figure 1 shows the experimental set-up. The modified fuel tank was instrumented with a 0.040-inch diameter Chromel-Alumel* thermocouple to measure the gas mixture temperature and with a strain-gage pressure transducer to monitor pressure during a firing; the output of the thermocouple was fed to a potentiometer, and that of the pressure transducer to an oscilloscope equipped with a camera. Six electrical strip heaters were evenly spaced around the fuel tank for heating the gas mixture when required. One end of the fuel tank was equipped with a gas inlet port, a rupture disk (1 mil brass), and an adaptor for the incendiary igniter assembly; the other end had an access port for gas sampling. The static pressure required to rupture the brass diaphragm was about 15 psig. Figure 2 is a photograph of the igniter assembly which was fabricated from a Conax fitting, having a 5/8-inch base and equipped with a 3/8-inch diameter electrode that was insulated by a phenolic sleeve. The IM-11 incendiary powder was loaded in the annular space within the Conax fitting. This fitting was covered with a cardboard compression ring and secured by a 1/16-inch plexiglass rupture disk and a locking nut. Ignition of the incendiary powder was effected by a 110 volt d.c. source after the material was packed so that its electrical resistance was not more than 30 ohms; the packing density was controlled by adjustment of the locking nut.

Experiments were conducted in the fuel tank under static conditions with near-stoichiometric n-pentane (2.2 to 2.4 volume percent)-air mixtures and various Halon inhibitor concentrations at $85^{\circ} \pm 5^{\circ}\text{F}$ and atmospheric pressure. To conduct an experiment, the test mixture was passed through the fuel tank for about three volume changes after which a gas sample was taken from the effluent and analyzed by gas chromatography to verify the composition of the mixture. The gas mixture was then ignited by firing the incendiary source, using incendiary charges of 0.55 g or larger. Since all ignition delays observed in these experiments were minimal (<2 milliseconds), the pressure rise data developed were relied upon to assess the ignition suppression effectiveness of the Halon agents.

Several runs were also made in the 74-gallon fuel tank in which mixtures were ignited by gun firings with 30-caliber incendiary (50 grains of IM-11) ammunition. In these experiments, the incendiary ammunition was fired into the middle of the fuel tank through a 1/4-inch steel striker plate. The gun firings were made with a 30-'06 rifle about 150 feet from the fuel tank; the projectile velocity was approximately 2800 ft/sec.

* Reference to specific trade names is made to facilitate understanding and does not imply endorsement by the Bureau of Mines.

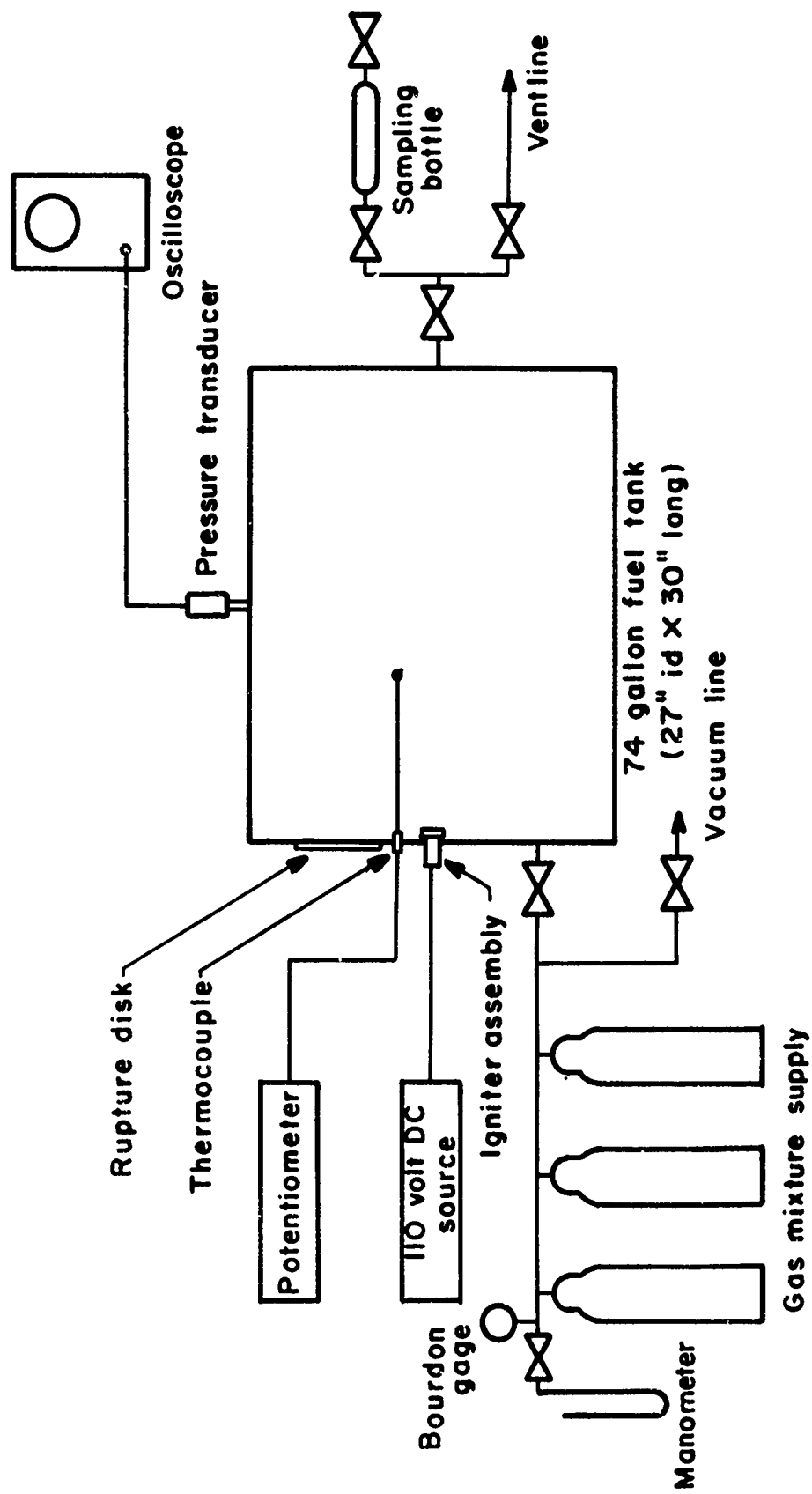


Figure 1 - Experimental setup for large-scale incendiary ignition experiments.

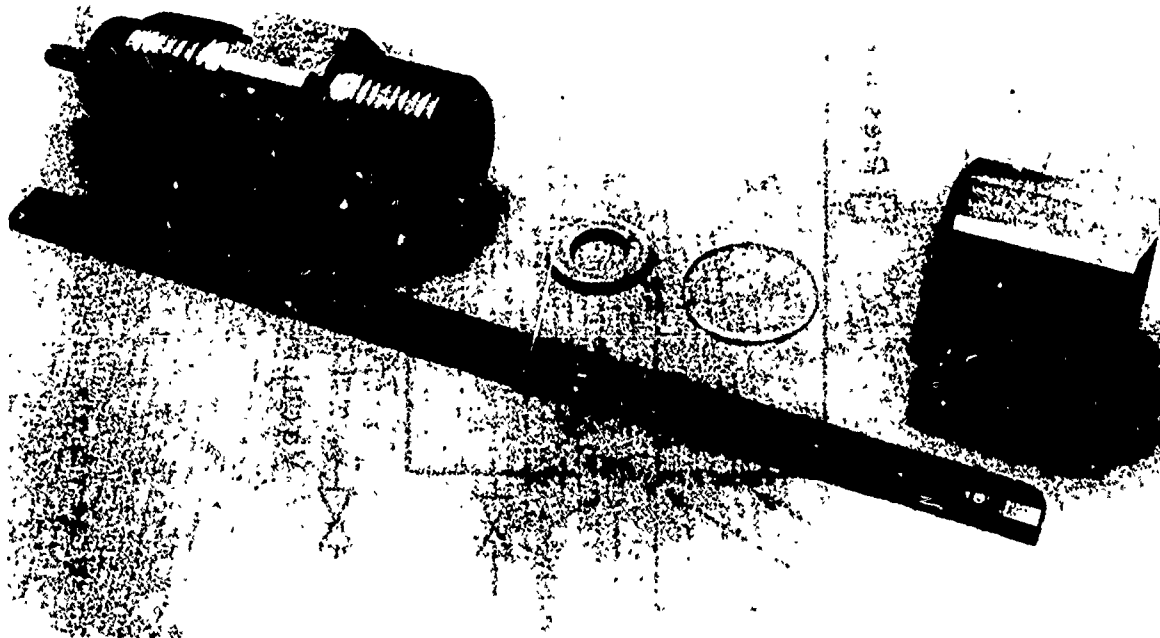


FIGURE 2. Incendiary powder igniter assembly.

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B. Total Flooding Fire Suppression Systems

Fire extinguishing experiments with Halon 3800 were conducted by the total flooding mode in a 216 ft³ chamber using cotton sheeting (5.1 oz/yd²) and "Sanidrape" paper sheeting (2.1 oz/yd²) as the combustibles. As shown in figure 3, the combustible was mounted on a rectangular rack suspended in the center of the chamber and ignited by a nichrome coil along the entire bottom edge of the specimen. The Halon was discharged from a 378 in³ commercial extinguisher bottle (Walter Kidde), pressurized to 350 psig with nitrogen, after a predetermined burning period. This extinguisher was actuated by firing a pyrotechnic charge which released the agent through a 1-1/2-inch pipe nozzle, directed towards a chamber wall at a 45° angle. The test chamber was instrumented for monitoring pressures and temperatures and for sampling combustion products during a run; motion pictures were also taken to record the burning and extinguishment.

Most experiments were made at a combustible loading of 0.035 oz/ft³ using a single rack, although a few were made at a loading of 0.070 oz/ft³. For the cotton sheeting, the 0.035 oz/ft³ loading was achieved by using two 36-by-27-inch sheets, as compared to four 36-by-42-inch sheets for the paper sheeting (2 ply); the higher loading was obtained by doubling the number of sheets. When two racks were used, they were spaced about one-foot apart and the combustible was equally divided.

The extinguisher charge was varied from 6.4 to 13.8 lbs to provide Halon 3800 concentrations of 6 to 12 volume percent in the test chamber. However, because of the limited capacity of the commercial extinguisher (~15 lbs), the use of the higher loadings would greatly reduce the available ullage and amount of nitrogen that could be added. Therefore, a nitrogen reservoir was added to insure that the pressure throughout the discharge would approximately correspond to that maintained in earlier work with Halon 1301.^{2/}

Gas samples were taken at 5, 60, and 240 seconds after the Halon discharge and analyzed for normal combustion products by gas chromatography; total fluorides were determined by a specific ion electrode method and are reported as HF. Details regarding the sampling system and analytical techniques are described in a previous summary report.^{2/}

A few total flooding experiments were conducted in the 216 ft³ test chamber using liquid nitrogen as the extinguishant. Cotton sheeting was the combustible at a 0.035 oz/ft³ loading on a single rack. The liquid nitrogen reservoir consisted of a 6.5-inch i.d. by 18-inch long cylindrical vessel, which was equipped with an adjustable overflow for regulating the volume of nitrogen and connected to a 600 psig helium reservoir for rapidly discharging of the system (figure 4). Upon opening the valve connecting the two vessels, the system pressure attained a value of only about 240 psig because of the low temperatures and ruptured the brass diaphragm for releasing the liquid nitrogen; normally, the diaphragm rupture occurred several seconds after opening the valve. The nitrogen

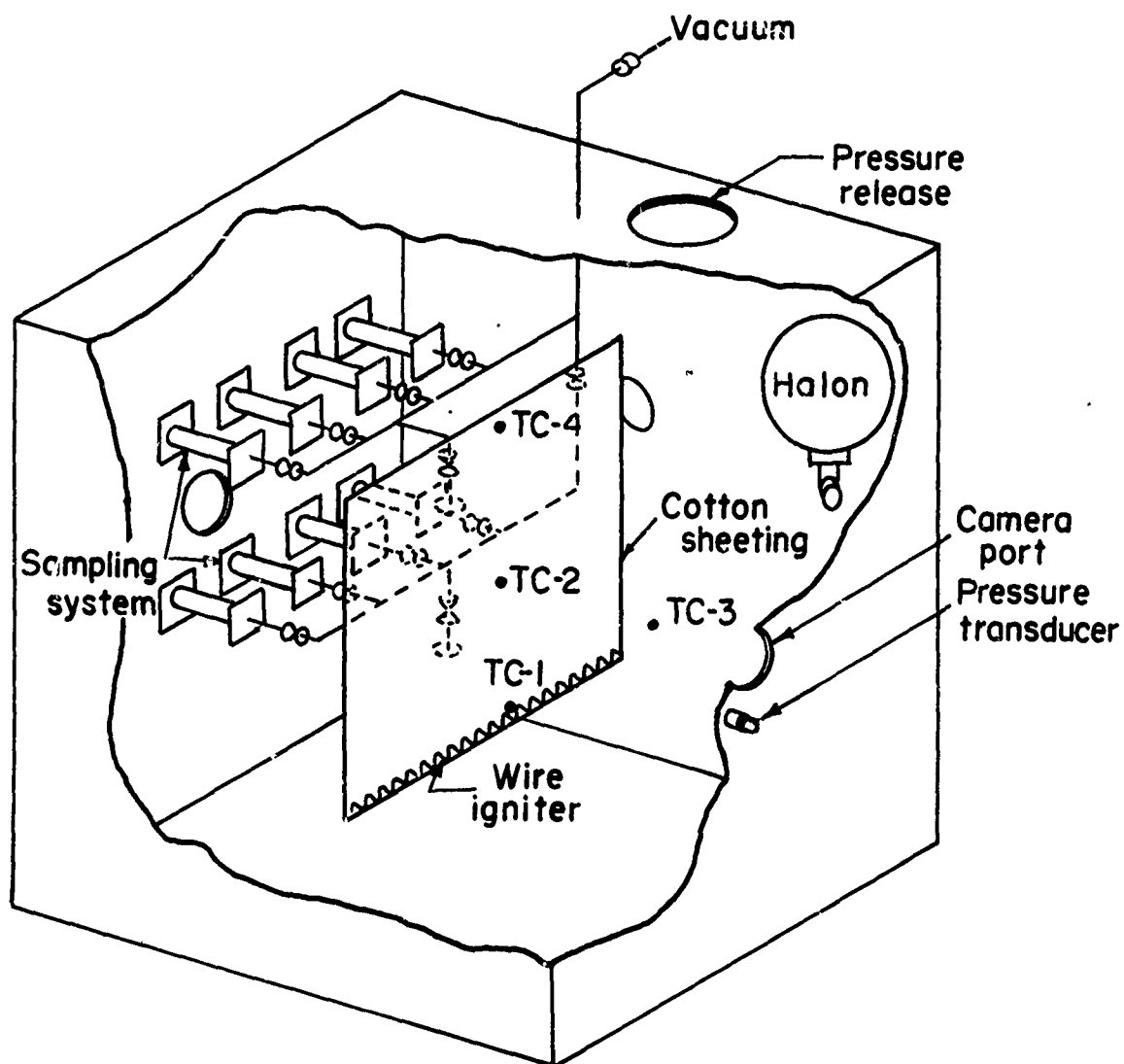


FIGURE 3. Sketch of experimental setup for fire extinguishing experiments in 6-foot cubical chamber (216 ft³).

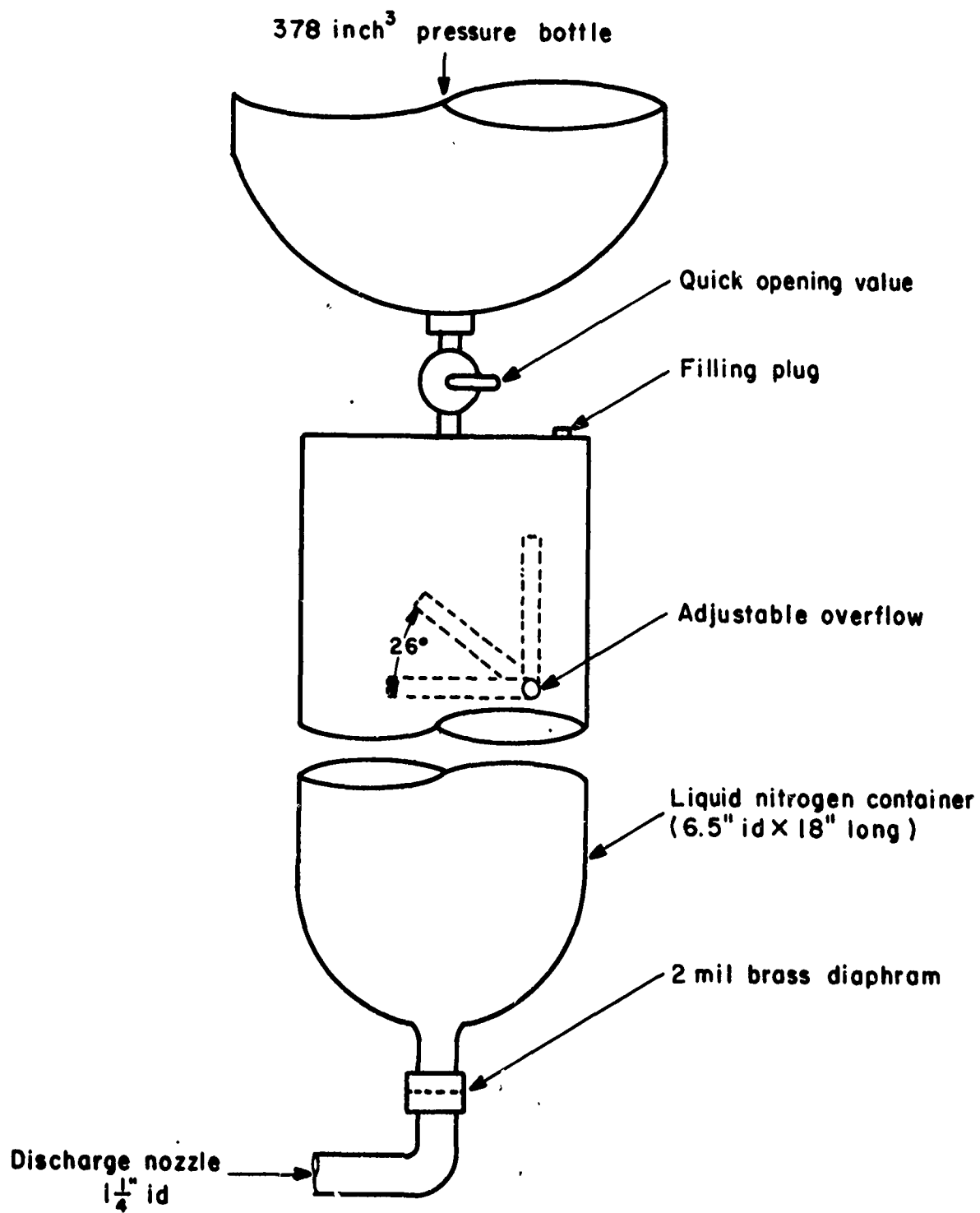


Figure 4— Liquid nitrogen discharge system.

was discharged through a 1-1/4-inch nozzle and against the wall of the test chamber, as in the Halon experiments. With this set-up, a maximum nitrogen concentration of approximately 40 percent could be obtained in the chamber. Because of the added nitrogen pressure and pressure limitations of the chamber (~15 psig), the experiments were limited to those where preburn times were not excessive.

RESULTS AND DISCUSSION

A. Ignition Inhibitors for Fuel Tank Protection

1. Ignitions with Incendiary Powder

Results obtained in the fuel tank incendiary ignitions revealed that the ignition suppression requirements for n-pentane-air mixtures did not differ greatly with the composition of the three Halons (1301, 1202, and 1211) investigated. Table I and figure 5 show the effect of Halon concentration on the rates of pressure rise from experiments in which near-stoichiometric (2.2-2.4%) n-pentane-air mixtures and the added Halons were ignited with 0.55 gram charges of the IM-11 incendiary powder. Both the initial and maximum rates of pressure rise decreased with increasing Halon concentration. The maximum pressure rises attained when the explosion relief diaphragm ruptured also decreased with increasing inhibitor concentration, although the results were not completely consistent since the diaphragm failure also depended upon the pressure rise rate. With Halon 1301, the maximum pressure rise rates decreased noticeably when the Halon concentration was increased from 0 to about 3.5 volume percent, above which the rates were less than 200 psi/sec. A Halon concentration greater than 8 percent was required to reduce the pressure rise to less than 5 psi and, thereby, provide an acceptable level of explosion suppression for this application. As indicated, the maximum pressure rise was only 3.2 psi and the corresponding rate of pressure rise was less than 15 psi/sec with 10 percent Halon 1301; in this case, the explosion relief diaphragm was not ruptured. According to calibration tests, pressure rises up to approximately 1.5 psi could be attributed to the burning of the incendiary (0.55 g). The corresponding quenching requirements with Halons 1202 and 1211 appeared to be over 7 percent, although the data were less complete for these inhibitors. With 7 percent concentrations of these Halons, the maximum pressure rise rates were only about 50 psi/sec, but the pressure rises were at least 10 psi.

The effect of the amount of incendiary powder in the above experiments was investigated using 0.55 to 1.5 gram incendiary charges and Halon 1301 (7 to 8 volume percent) as the inhibitor. Although the Halon concentration was not constant, this was not serious considering the trend of pressure rise data for the 0.55 gram charge weight (figure 5). It is evident from the results in Table II that the effect of igniter weight on inhibition effectiveness is rather small when the incendiary charge is increased from 0.55 to 1.0 gram. However, with a further increase to 1.5 grams, the initial and maximum pressure rise rates appeared to double at least; also, the time to attain maximum pressure was substantially reduced. Obviously,

TABLE I. - Pressure Rise Data from Large-Scale Incendiary Ignition Experiments in a 74-Gallon Fuel Tank With Halons 1301, 1211 and 1202 and Approximately Stoichiometric n-Pentane-Air Mixtures at Atmospheric Pressure.

Incendiary Composition (IM-11) - 0.55 gm

Added Halon Vol. %	Pressure Rise			Time to P _{max} sec
	(dp/dt) initial psi/sec	(dp/dt) max psi/sec	P _{max} ^{1/} psi	
<u>Halon 1301</u>				
0	1535	1535	51.5	0.040
1.6	95	470	25.0	.128
3.5	55	226	17.9	.115
3.5	--	107	16.8	.160
4.0	55	98	14.7	.185
7.6	32	112	12.5	.228
8.0	27	94	17.5	.364
10.0	14	14	3.22/	.768
<u>Halon 1211</u>				
3.5	110	211	21.1	0.117
7.0	19	46	12.6	.500
<u>Halon 1202</u>				
4.0	46	128	12.6	0.125
7.0	35	54	10.0	.170

1/ Maximum pressure rise at time of rupture of explosion relief diaphragm.

2/ No rupture of explosion relief diaphragm.

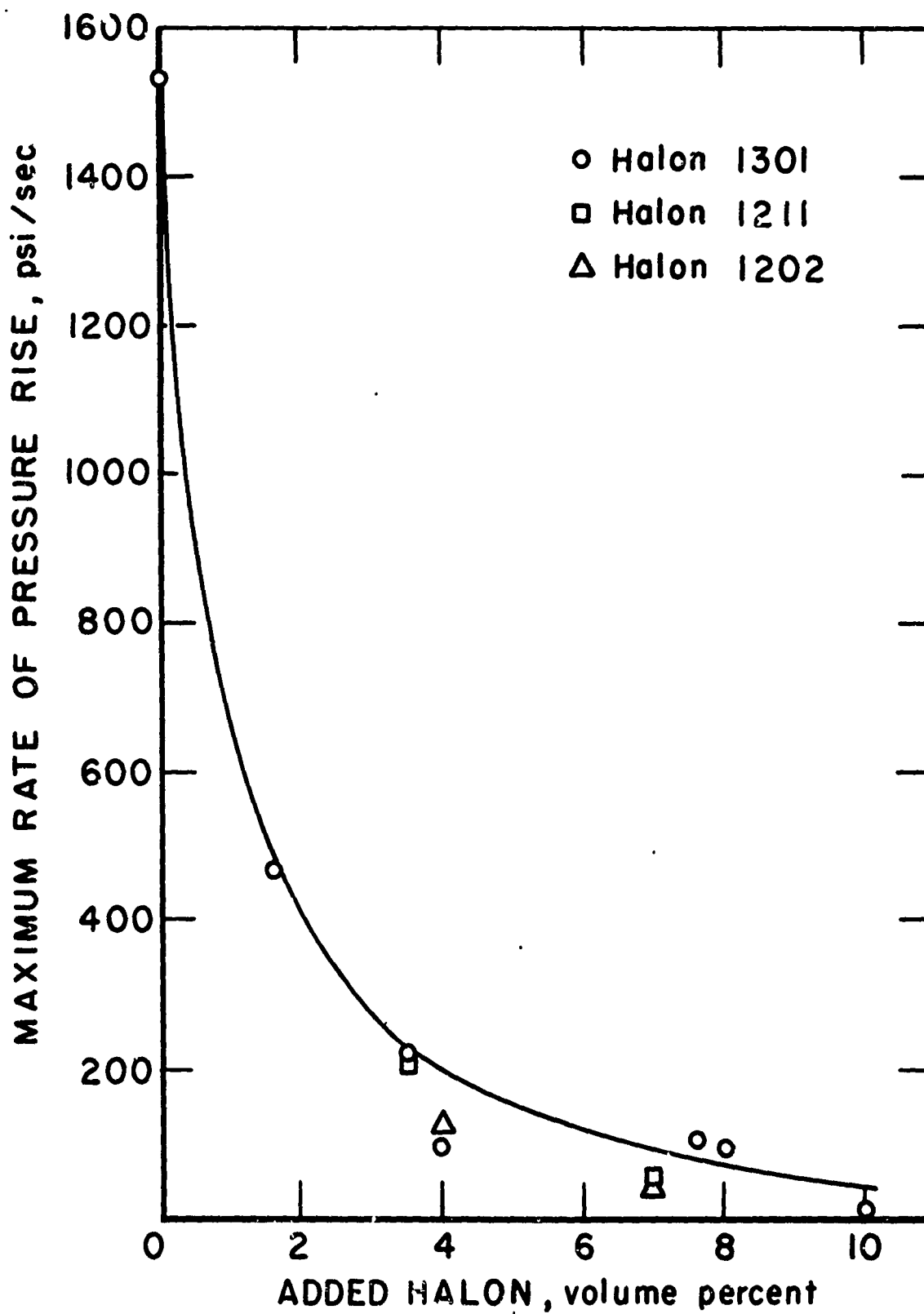


FIGURE 5 Maximum rate of pressure rise vs Halon concentration for fuel tank ignitions of near-stoichiometric n-pentane-air mixtures (1 atm) and various Halons with an incendiary powder (0.55 gram IM-11).

TABLE II. - Effect of Igniter Weight on Rates of Pressure Rise in Large-Scale Incendiary Ignition Experiments in a 74-Gallon Fuel Tank With Halon 1301 and Approximately Stoichiometric n-Pentane-Air Mixtures at Atmospheric Pressure.

Incendiary Composition (IM-11) - 0.55 gm

Added Halon Vol. %	Weight of Incendiary Powder gram	Pressure Rise			Time to P_{max} sec
		$(dp/dt)_{initial}$ psi/sec	$(dp/dt)_{max}$ psi/sec	$\Delta P_{max}^{1/}$ psi	
8.0	0.55	27	94	17.5	0.368
7.6	0.55	32	112	12.5	0.228
7.8	1.0	41	96	13.7	0.200
7.2	1.0	40	55	10.1	0.213
7.0	1.5	152	193	16.0	0.098

^{1/} Maximum pressure rise at time of rupture of explosion relief diaphragm.

the effect of the igniter weight on explosion pressure development will depend upon the size of the container in which the ignition occurs.

According to the present results, the effectiveness of the three Halon inhibitors in suppressing incendiary ignitions of n-pentane-air mixtures varies more noticeably with the concentration of inhibitor than with its composition. Also, the critical Halon concentrations for quenching tend to be high compared to those found with a localized ignition energy source, such as an electric spark. With the latter ignition source, concentrations of less than 5 volume percent of Halons 1301, 1211, or 1202 are required for inerting methane-air flames at atmospheric pressure;^{3/} about the same concentrations are necessary for the flames of higher molecular weight paraffins, such as n-pentane, n-hexane, or n-heptane.^{4/} Since the inerting or quenching requirements do not vary greatly with the composition of hydrocarbon type fuels, the data presented in this report can be used to predict the approximate concentrations of the given Halons for protecting against fuel tank ignitions involving aircraft jet fuels. In all cases, the Halon requirements are much less severe than those found with the use of an inert gas, such as nitrogen or carbon dioxide.

2. Ignitions with Gun Firings

The inhibitor effectiveness of Halon 1301 was also examined in a few gun firing experiments in which near-stoichiometric n-pentane-air mixtures were ignited in the fuel tank with 30-caliber incendiary ammunition (50 grains). The pressure rise data from the gun firing experiments with test mixtures containing 0, 1.8, and 9.7 volume percent Halon 1301 are compared in Figure 6 and Table III with the results obtained using the igniter assembly with 0.55 gram charges of the incendiary powder and approximately the same inhibitor concentrations. Except for the runs with no Halon inhibitor, the rates of pressure rise at the given Halon concentrations tended to be somewhat higher in the trials with the incendiary ammunition. As noted, the maximum rate of pressure rise in the gun firings decreased from 693 to 43 psi/sec when the inhibitor concentration was increased from 1.8 to 9.7 volume percent. In comparison, the corresponding rates in the experiments with the incendiary igniter (0.55 gram) chamber were 470 and 14.0 psi/sec at Halon 1301 concentrations of 1.6 and 10.0 volume percent, respectively. It is also noted that at the highest Halon concentration, the time to attain maximum pressure was much shorter when ignition was initiated by gun firing; nevertheless, complete quenching was achieved regardless of the ignition source.

^{3/} Burgess, D. S. and J. M. Kuchta. Effectiveness of Halogenated Agents Against Gaseous Explosions and Propellant Fires, Symposium on Appraisal of Halogenated Fire Extinguishing Agents, Nat'l. Academy of Sciences, April 1972.

^{4/} Purdue University, Final Report on Fire Extinguishing Agents, Contract W44-009-eng 507, Army Engrs. Res. & Dev. Labs, June 30, 1950.

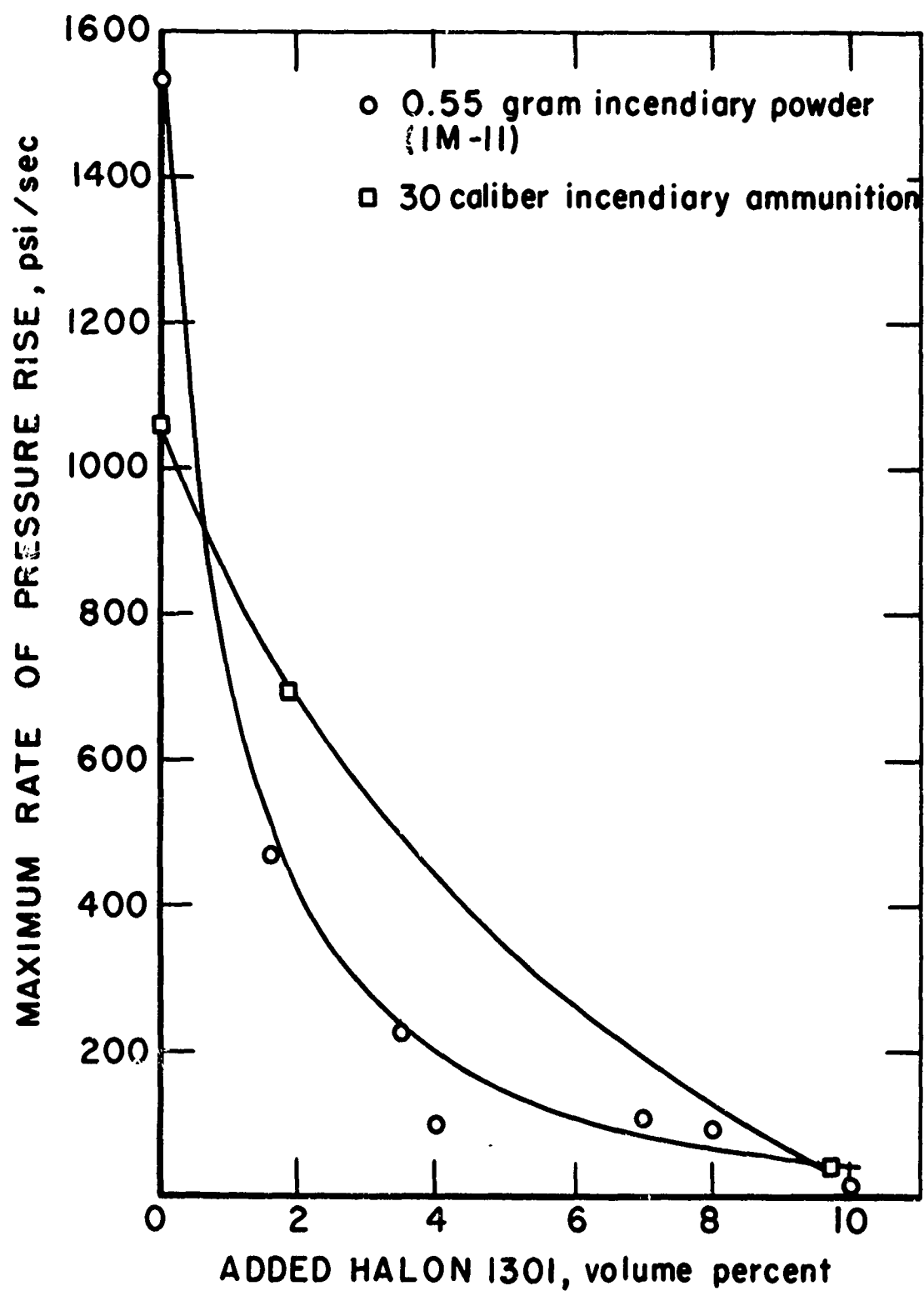


FIGURE 6. Maximum rate of pressure rise vs Halon 1301 concentration for fuel tank ignitions of near-stoichiometric n-pentane-air mixtures (1 atm) and Halon 1301 with 30-caliber incendiary (50 grains) ammunition and 0.55 gram charges of incendiary powder.

TABLE III. - Comparison of Pressure Rise Data From Large-Scale Gun Firing (30-Caliber Incendiary Ammunition) and Incendiary (0.55 gram) Ignition Experiments in a 74-Gallon Fuel Tank With Halon 1301 and Near-Stoichiometric n-Pentane-Air Mixtures at Atmospheric Pressure.

Added	Pressure Rise			Time to
Halon	(dp/dt) _{initial}	(dp/dt) _{max}	$\Delta P_{\text{max}}^{1/}$	P_{max}
Vol. %	psi/sec	psi/sec	psi	sec
Gun Firings				
<u>30-Caliber Incendiary (50 grains Ammunition)</u>				
0	1059	1059	39.0	0.060
1.8	140	693	27.3	0.103
9.7	43	43	1.2 ^{2/}	0.100
Firings With Igniter Assembly				
<u>0.55 Gram Incendiary Powder</u>				
0	1533	1533	51.5	0.040
1.6	95	470	25.0	0.128
10.0	14	14	3.2 ^{2/}	0.768

1/ Maximum pressure rise at time of rupture of explosion relief.

2/ No rupture of explosion relief diaphragm.

Table IV summarizes the Halon 1301 requirements that have been obtained for quenching approximately stoichiometric n-pentane-air ignitions under various ignition conditions. The small-scale experimental data were reported previously^{2/} and show the misleading conclusions that could result from the use of a marginal ignition source, such as a heated platinum wire, that is limited by its temperature. On the other hand, the Halon quenching requirement for ignitions with an exploding wire is similar to that found with the IM-11 incendiary powder under laboratory-scale conditions. Furthermore, the laboratory results with these two energy sources appeared to be nearly comparable to those obtained in the large-scale incendiary ignitions in a 74-gallon fuel tank. Since the quenching requirements will generally increase with increased igniter energy flux, the results from single gun firings are not applicable to multiple gun firings without allowing for the effect of additional ignition sites.

B. Total Flooding Fire Suppression Systems

1. Halon 3800

The large-scale extinguishing experiments with cotton sheeting fires at a loading of 0.035 oz/ft^3 (1 rack) indicated that a 6 percent Halon 3800 concentration is relatively ineffective against such fires. Table V summarizes the data from the experiments conducted in the 216 ft^3 test chamber using both cotton and paper sheeting. With the cotton sheeting and a preburn period of 25 seconds, a 6 percent Halon concentration was not very effective since the burning was sustained for 30 seconds after the Halon application and 90 percent of the combustible was consumed; about 60 percent combustible would normally be consumed after such a preburn period.^{2/} With 10 or 12 percent concentrations at the same preburn time, the burning appeared to be rapidly extinguished (1-1/2 seconds). However, on opening the chamber after 15 minutes, the combustible (mostly char) was still glowing and again at least 90 percent was consumed. Only when the preburn time was reduced to 15 seconds or less was rapid and complete extinguishment achieved at this combustible loading. In comparison, a 6 percent Halon 1301 concentration and a 25 second preburn time were previously found to provide total extinguishment in less than 1 second with only 65 percent of the cotton sheeting consumed.^{2/}

At a higher cotton sheeting loading of 0.07 oz/ft^3 , rapid and complete extinguishment was achieved after a short preburn time (10 seconds) using 10 or 12 percent Halon 3800; similar success had been obtained with Halon 1301 at lower concentrations. However, at a 20 second preburn time, incandescent burning was again observed after extinguishing the flames with the perfluorinated hydrocarbon. It is apparent that this Halon would be useless against most deep-seated fires, although no vaporizable extinguishants are recommended per se for such fires.

In the extinguishing experiments with paper sheeting fires, a combustible loading of 0.035 oz/ft^3 was used with burning on single and double

TABLE IV. - Halon 1301 Requirement for Quenching Approximately Stoichiometric n-Pentane-Air Ignitions Under Various Ignition Conditions at Atmospheric Pressure.

Test Chamber	Ignition Source	Critical Halon 1301 Concentrations	
		Vol. %	
Fuel tank (74 gal)	IM-11 incendiary powder - 0.55 gram	9-10	
	30-caliber incendiary ammunition - 50 grains	9-10	
Small vessel (1.3 gal) ^{1/}	IM-11 incendiary powder - 0.17 gram	8	
	Pyrofuze exploding wire - 0.005 in diam by 1-1/4 in long	8	
	Platinum wire (2070°F) - 0.016 in diam by 1-1/4 in long	1	

^{1/} Data from reference 2.

racks. Here, the Halon was injected after a preburn period of only 6 or 8 seconds, corresponding to the time when the burning was near its peak. Both 12 percent and 10 percent Halon 3800 concentrations gave complete extinguishment of burning on single and double racks, respectively, within one second. Lower extinguishant concentrations were not investigated with this combustible.

Based on previous small-scale experiments, the main toxic products investigated were carbon monoxide (CO) and hydrogen fluoride (HF). Since the CO formation was primarily dependent upon the amount of combustible burned, the extinguishing experiments with the longer preburn periods yielded the highest CO concentrations. The toxic product data are included in Table V. With either the cotton sheeting or paper sheeting fires, the CO was not greater than 2000 ppm. These maximum CO concentrations are above the threshold limit value (TLV)^{5/} of 50 ppm, which can cause some ill effects for extended exposure periods, but are far below the approximate lethal concentration (ALC)^{6/} of 15,000 ppm reported for 15 minute exposure periods.

The HF concentrations produced in the present study with Halon 3800 were noticeably higher than the total halogen acid concentrations produced in similar experiments with Halon 1301^{2/} under essentially the same fire conditions. This was largely due to the fact that higher Halon 3800 concentrations were required for extinguishing the fires. The highest HF concentrations (1000-2500 ppm) occurred in extinguishing the cotton sheeting fires with long preburn time and in the paper sheeting fires which were investigated only under peak burning conditions. Under such burning and extinguishing conditions, the toxicity hazard due to HF could be serious since the ALC value for 15 minutes of exposure is 2500 ppm. These results generally confirm those from the small-scale experiments.^{2/} Essentially, Halon 3800 is less effective than Halon 1301 and produces a greater toxicity hazard in extinguishing such Class A fires.

2. Liquid Nitrogen

Two total flooding experiments were initially conducted in the 216 ft³ chamber to obtain reference data with the liquid nitrogen dispersal system. Table VI summarizes the pressure rise data and gas analyses from experiments designed to yield 35 and 40 volume percent added nitrogen in the chamber. After ignition, a considerable portion of the liquid nitrogen appeared to accumulate on the floor of the chamber until vaporized. According to the pressure rises, approximately 30 seconds was required to attain 90 percent of the final pressure (>6 psig) at the lower N₂ loading and 22 seconds at the higher loading. Complete vaporization of

^{5/} Threshold Limit Values for 1970, American Conference of Governmental Hygienists.

^{6/} National Fire Protection Association, Standard on Halogenated Fire Extinguishing Agent Systems, NFPA No. 12A, 1971.

TABLE V. - Data from Fire Extinguishing Experiments with Perfluoropropane (Halon 3800) and Cotton or Paper Sheetting Fires in a 216 ft³ Chamber.

Halon Vol. %	Combustible Loading oz/ft ³	Preburn Time sec.	Material Consumed wt. %	ΔP _{max} psi	Exting. Time sec.	Gas Analyses			
						Halon, vol. %	CO, ppm	HF, ppm	
						240 sec.	240 sec.	5 sec	240 sec
<u>Cotton Sheetting</u>									
6	0.035	25	90	6.2	30	4.0	2000	660	275
10	0.035	25	92	7.5	1.0 ^{1/}	9.1	1000	2475	225
12	0.035	25	>90	7.1	1.3 ^{1/}	9.9	600	325	375
10	0.035	10	65	6.1	<1	9.5	<100	1495	835
(2 racks)									
12	0.035	15	16	2.0	0.8	9.3	<100	196	360
10	0.070	20	>24	3.2	>15 ^{1/}	10.4	1000	2329	1224
12	0.070	10	7	1.8	0.3	11.4	400	30	250
<u>Paper Sheetting</u>									
10	0.035	6	80	9.0	1.0	9.3	200	1660	1440
(2 racks)									
12	0.035	8	78	8.9	0.6	11.9	2000	1470	1265

^{1/} Incandescent burning continued after flame extinguishment.

TABLE VI. - Pressure Rise Data and Gas Analyses from Dispersion Experiments with Liquid Nitrogen Total Flooding System in a 216 ft³ Chamber.

Added N ₂ Vol. %	50% ΔP _{max}		90% ΔP _{max}		ΔP _{max}		ΔT		Time sec.	Gas Analyses		
	psi	sec	psi	sec	psi	sec	°F	sec		O ₂	N ₂	He
35	3.1	4	5.6	30	6.2	85	-120	4	5	12.6	85.1	2.3
							- 45	30	240	13.5	84.4	2.1
40	3.2	4	5.8	22	6.4	55	-105	4	5	12.8	85.5	1.7
							- 60	30	240	12.3	85.5	2.2

TABLE VII. - Pressure Rise Data and Gas Analyses from Liquid Nitrogen Total Flooding Experiments With Cotton Sheeting (0.035 oz/ft³) Fire in a 216 ft³ Chamber.

Added N ₂ Vol. %	Preburn Time		Material Consumed Wt. %	ΔP (Preburn)		Extng. Time		ΔP _{max}		Time		Gas Analyses		
	sec.	sec.		psi	psi	sec.	sec.	psi	psi	sec.	sec.	O ₂ Volume %	N ₂ He	CO CO ₂
30	18	18	58	---	---	10	---	---	---	5	12.6	84.0	2.4	1.0 0.08
										240	13.1	83.9	1.9	1.1 0.09
35	18	18	28	1.6	---	<1	---	6.6	---	5	13.8	82.9	2.8	0.5 0.03
										240	14.0	83.1	2.3	0.6 0.03
40	18	18	26	2.7	---	<1	---	7.5	---	5	13.2	84.0	1.9	--- ---
										240	12.6	84.3	2.3	--- ---

1/ Elapsed time after preburn period.

the N₂ was prolonged since the temperature dropped over 100°F within 4 seconds after injection and recovered only about half this drop within 30 seconds. The oxygen concentration after 240 seconds was 13.5 percent for the lower N₂ loading and 12.3 percent for the higher loading.

Extinguishing experiments with the liquid nitrogen system were made with cotton sheeting fires at a combustible loading of 0.035 oz/ft³ (1 rack) and a preburn of 18 seconds. Table VII shows the data obtained using 30, 35, and 40 percent nitrogen. The 30 percent N₂ dilution was hardly effective since the extinguishing time was 10 seconds and 58 percent of the combustible was consumed; 25-30 percent consumption would be expected after an 18 second preburn time.^{2/} In comparison, both of the higher N₂ concentrations provided rapid extinguishment (<1 second) under the same condition and limited the burning to less than 30 percent of available combustible; total N₂ was between 83 and 85 percent and the CO or CO₂ formation was lower than in the trial with 30 percent N₂. Figure 7 compares the pressure rise development obtained with the 35 percent added N₂ in experiments with and without the cotton sheeting fires. In the extinguishment test, the nitrogen vaporized much more rapidly because of the added heat to the chamber during the preburn period. Also, because of the rapid extinguishment, the maximum pressure rise was not much higher than that produced by the added N₂ in the absence of fire.

The high N₂ concentrations required for extinguishment are not unexpected considering that similar concentrations of this gas are also necessary to inert many hydrocarbon fuel-air systems. As a result of the high agent requirements, corresponding oxygen concentrations are low and therefore, preclude the use of N₂ total flooding systems in occupied compartments because of the asphyxiation hazard. Furthermore, the agent requirements can vary with combustible composition, combustible orientation, and fire scaling parameters. Information on the effects of these variables is essential in determining the potential of such an extinguisher system for any contemplated use.

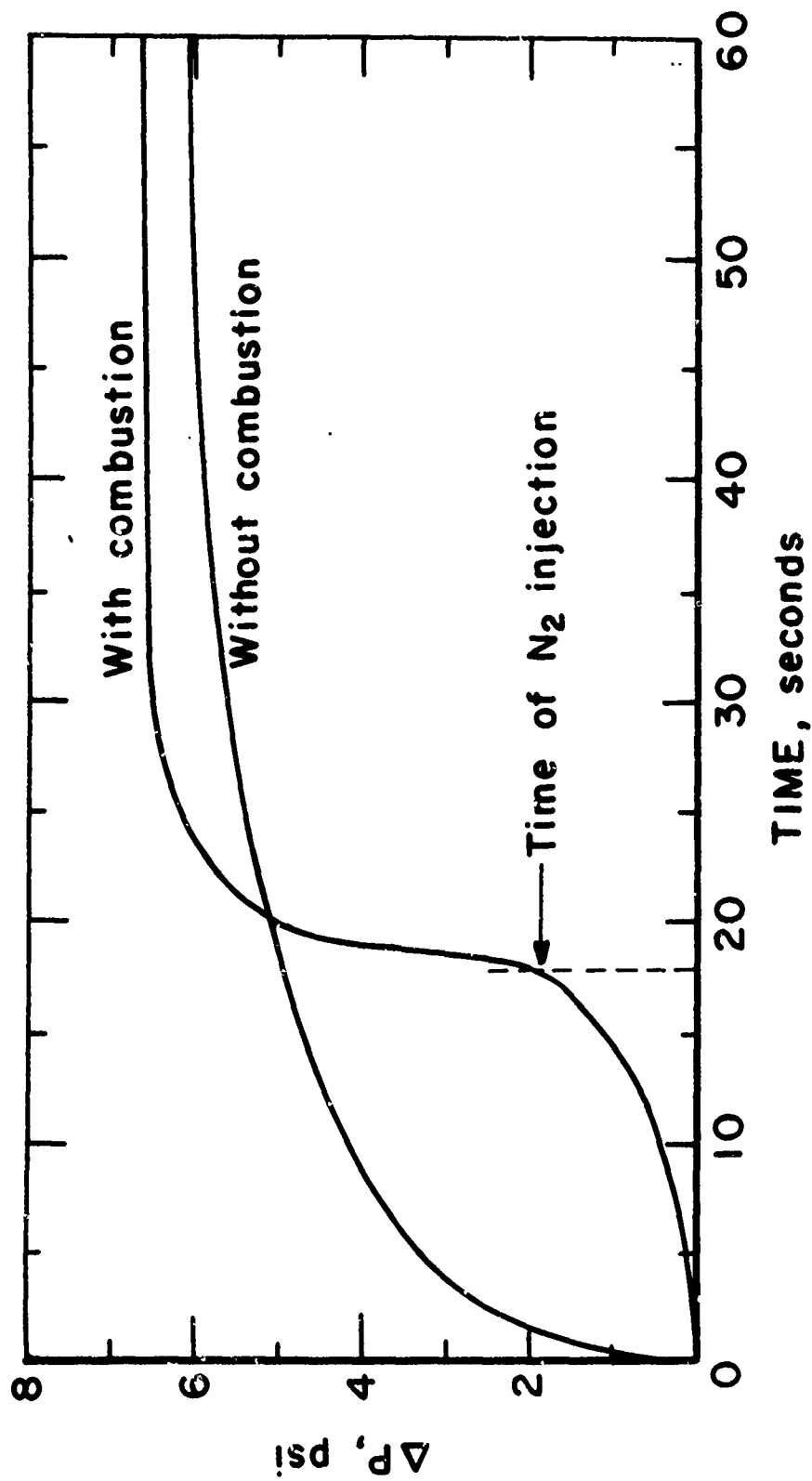


FIGURE 7. Pressure rise vs time in liquid nitrogen total flooding experiments with and without cotton sheeting (0.035 oz/ft³) fire in a 216 ft³ chamber (Added N₂ - 35 percent).

CONCLUSIONS

The effectiveness of Halons 1301, 1202, and 1211 in suppressing incendiary ignitions of n-pentane-air mixtures varies more noticeably with the concentration of the Halon inhibitor than with its composition. Over 8 volume percent Halon 1301 was required for complete quenching of near-stoichiometric n-pentane-air explosions that were initiated with 0.55 gram charges of the IM-11 incendiary powder in a 74 gallon fuel tank. The corresponding quenching requirement with Halon 1202 or 1211 was somewhat over 7 percent, the maximum concentration used with these two Halons. Similar high inhibitor concentrations were also required under gun firing conditions where the fuel tank explosions were initiated with 30-caliber incendiary ammunition and quenched with Halon 1301. These critical Halon concentrations were high compared to those for ignitions of such flammable mixtures with an electric spark or heated wire. However, for ignitions by multiple gun firings, the critical Halon values would tend to be even higher than those reported here.

Halon 3800 concentrations of 10 to 12 volume percent appeared to be adequate for extinguishing cotton sheeting and paper sheeting fires when the combustibles were mounted vertically and the agent was dispersed by the total flooding mode. However, incandescent burning could occur after flame extinguishment, particularly in the case of cotton sheeting fires at long preburn times. Also, the maximum HF concentrations that were produced were comparable to the approximate lethal values (ALC's) reported for 15 minute exposure periods. Generally, Halon 3800 is less effective than Halon 1301 and produces a greater toxicity hazard in extinguishing such Class A fires. Both of these Halons were much more effective than liquid nitrogen, whose effectiveness was investigated in a few total flooding experiments with cotton sheeting fires.

RECOMMENDATIONS

In order to evaluate other fire or explosion suppression systems which may be more suitable for certain aircraft applications because of increased effectiveness or reduced toxicity hazard, the following recommendations are made for future work:

- (1) Investigate total flooding systems utilizing the "hot bottle" technique for dispersal of the extinguishant. Determine quenching requirements and toxic product formation for Class A fires with various Halon extinguishers (including Halon 1301) that are designed to disperse and vaporize the Halon by generation of hot propellant gases.
- (2) Investigate liquid nitrogen-Halon extinguisher systems using Halon 1301 and other promising agents. Determine burning velocities of hydrocarbon fuel-air flames as a function of nitrogen-Halon concentrations at atmospheric pressure. Also, determine quenching requirements for simulated fuel tank ignitions and Class A fires.